STAMPING OF WOVEN FABRIC REINFORCED THERMOPLASTIC COMPOSITES

Woong-Ryeol Yu, Michael A. Zampaloni , and Farhang Pourboghrat
Department of Mechanical Engineering, Michigan State University

Abstract

This study is to investigate the feasibility of shaping preconsolidated woven fabric reinforced thermoplastics using sheet hydroforming, as being a new forming method for composite manufacturing. For that purpose, a new constitutive model has been developed based on a homogenization method considering the microstructures of composites including mechanical and structural properties of fabric reinforcement.

The current model aims to account for the effect of the fiber strength difference and orientation on anisotropy and also to simulate shear deformation with no length change, which is common in FRT composite forming. For validation purposes, the developed model was implemented in an explicit dynamic finite element code and tested for several deformation modes including pure shear as well as three-dimensional deformation mode.

Introduction

Fabric reinforced composites are now gaining popularity in manufacturing automotive and aerospace parts due to their good reinforcing properties, ease of handling and well established textile technologies [1]. Fabric reinforcements fabricated into composites with the thermoplastic resin not only improve mechanical and physical properties but also their chemistry enables rapid automated production of composite structures.

Numerous manufacturing processes have been proposed over the years to shape thermoplastic composites, ranging from injection molding to diaphragm forming and filament winding. Due to their high success with metals, various attempts also have been made to apply sheet-stamping techniques to composites [2-3]. A difficulty to overcome in applying sheet-stamping for fabric-reinforced composites is the limited draping capability of fabrics, which are prone to wrinkle. Therefore, there exists a current need to develop appropriate constitutive equations for proper analysis and design of manufacturing processes of FRT composites with reduced wrinkling.

There are two common approaches in developing constitutive equations for FRT composites: continuum and meso-cell approaches. In the continuum approach, the global deformation behaviors are modeled with the phenomenological expression of the constitutive equation under the frame work of continuum mechanics, while in the meso-cell approach, the constitutive equation considers the micro-structural interaction between the matrix and the reinforcement using trusses and shell elements [4]. Therefore, the meso-cell approach can account for the evolution of the microstructures such as fiber angles. However, this approach takes too much of computation to analyze forming processes. The continuum approach is advantageous over the meso-cell approach in computational cost. However, it needs proper internal variables that account for major micro-structural evolution.

Many continuum models have been developed for orthotropic composites and they assume the preservation of the initial orthotropy during forming. Assuming the preservation of initial anisotropy, which is a common practice in sheet metal forming analysis, however is no longer proper for FRT composites since the fiber angle change is significant during FRT forming [5].

Recently, the ‘Idealized Fiber Reinforced Materials’ theory for fabric reinforced fluids was developed as a non-orthogonal continuum constitutive equation with inextensibility and incompressibility [6]. It was not proved however that this model is suitable for the finite element analysis of FRT forming processes. Therefore, a new continuum constitutive equation was developed here for FRT composites based on a homogenization method, which enables the prediction of preferred (fiber) orientation evolution.

Constitutive Equation

To develop a convenient tool to better understand physical source of the anisotropy in the constitutive equations of composites, a structural unit comprised of a pair of warp and weft fibers with pined joints is considered as shown in Figure 1. Intersection points of warp and weft fibers can rotate freely. Here, fibers are attached to the resin matrix and the structural unit shares a common uniform strain. By applying mechanical properties to the fibers and the matrix, total force and stresses are calculated considering the information on the structural parameters (thickness, structural unit dimension and fiber angle) and fiber properties. The material stiffness (relating strains and stresses) is then calculated using the kinematics and force equilibrium of the structural unit. The details on the derivation of current constitutive equation can be referred in a paper [7]. Here, the final form is presented to explain the difference between current constitutive form and other forms such as isotropic and orthotropic elastic equation

(Equation (1)).

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}\frac{\tilde{E}^{\alpha}}{bc}+\Gamma\left(\frac{a}{\bar{h}}\right)\left(\frac{a^2}{c}\right) & \Gamma\left(\frac{a}{\bar{h}}\right)\left(\frac{b^2}{c}\right) & \Gamma\left(\frac{a}{\bar{h}}\right)\left(\frac{ab}{c}\right)\\ \Gamma\left(\frac{b}{\bar{a}}\right)\left(\frac{a^2}{c}\right) & \Gamma\left(\frac{b}{\bar{a}}\right)\left(\frac{b^2}{c}\right)+\frac{\tilde{E}^{\beta}}{ac} & \Gamma\left(\frac{b}{\bar{a}}\right)\left(\frac{ab}{c}\right)\\ \Gamma\left(\frac{b}{\bar{h}}\right)\left(\frac{a^2}{c}\right) & \Gamma\left(\frac{b}{\bar{h}}\right)\left(\frac{b^2}{c}\right) & \Gamma\left(\frac{b}{\bar{h}}\right)\left(\frac{ab}{c}\right)\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ 2\varepsilon_{xy}\end{bmatrix} \tag{1}$$

where $\tilde{E}^{\alpha}=E^{\alpha}A^{\alpha}$, $\Gamma=A^{\gamma}E^{\gamma}\big/\left(a^2+b^2\right)^{3/2}$ and c is thickness of composites. The structural parameters in Equation (1) are defined in Figure 1, while E and A are the young's modulus and area of yarn in woven fabric, respectively. Note that the constitutive equation is symmetric since

$$\Gamma\left(\frac{a}{\bar{h}}\right)\left(\frac{b^2}{c}\right)=\Gamma\left(\frac{b}{\bar{a}}\right)\left(\frac{a^2}{c}\right),\ \Gamma\left(\frac{a}{\bar{h}}\right)\left(\frac{ab}{c}\right)=\Gamma\left(\frac{b}{\bar{h}}\right)\left(\frac{a^2}{c}\right) \tag{2}$$

In Equation (1), $\tilde{E}^{\beta}$ is added to account for the jamming and frictional effect of fabric structure. This idea treating the jamming and frictional effect is originated from the fact that the fictitious fibers orthogonal to the α fibers can prevent α and γ fibers from being too close unrealistically. The values may be determined to be a nonlinear function of the fiber angle from experiments such as the picture frame shear test (6), but a constant (10.0) is used here.

Quite often, the existence of the resin is ignored in modeling composites because the resin property is much less stiff compared to the reinforcement property. In the thermoforming process of thermoplastic composites, the role of resin is more important since the heat generated during forming changes the phase of the resin into a molten state, thus enabling the rheological flow of the resin and the reinforcement. Therefore, it might be necessary to model the resin material as a viscous material. But, since the current study focuses on the development of the constitutive equation and its validation, the resin property is assumed an isotropic elastic material under the plane stress condition with $\nu=0.5$. Therefore, the constitutive equation for the resin matrix under the plane stress condition is

$$\begin{aligned}&\sigma_{11}=\frac{E}{(1+\nu)(1-2\nu)}\left((1-2\nu)\varepsilon_{11}\right)=\frac{2E}{3}\varepsilon_{11},\\ &\sigma_{22}=\frac{2E}{3}\varepsilon_{22},\ \sigma_{12}=\frac{2E}{3}\varepsilon_{12},\ \sigma_{33}=0,\end{aligned} \tag{3}$$

This equation is combined with Equation (1) into the constitutive equation for FRT composites.

Implementation of the Constitutive Equation

To predict the overall deformed shape of a FRT during forming, the developed constitutive equation was implemented in the ABAQUS explicit code using the user material subroutine (VUMAT). The constitutive equation described so far is suitable for implementation in any finite element analysis packages in that the equation is given as an explicit matrix form. This feature is crucial for incorporating specific phenomena such as contact and thermal effects into forming process analysis.

It is assumed that every material points have two vector quantities ($\vec{a}$ and $\vec{b}$) expressing the sizes and directions of two families of fibers, which are main internal variables for the constitutive equation. These vectors are updated using the deformation gradient from incremental deformation. Note that updating of material direction using the rotation tensor results in preserving material directions.

Two direction vectors determine important parameters such as the fiber angle and projected length of the fiber as shown Figure 1. Using Equation (1), the updated stress–strain law is constructed by the parameters before further calculation of the stress increment. Note that Equation (1) is expressed in the materially embedded coordinate system aligned with the α fiber direction.

Results and Discussion

For validation purposes, simulation was performed for the first example having the shear boundary force on the right-hand side edge while the left-hand one was fixed, which resulted in deformation as shown in Figure 2. A total of 15 x 20 rectangular elements (CPS4 element in ABAQUS) were used with the material properties summarized in Table I. Figure 2 shows that the inextensibility condition forces the right-hand side edge to move inwards, thus the beam forms into a curved shape and compressive deformation developing on both top and bottom surface near the left-hand side edge. This deformed shape agrees very well with the kinematically admissible deformation shape, which was obtained using inextensibility in two directions and compressibility by Spencer [9]. Note that the current simulation result is quite different from those obtained under the same loading condition using the concept of the 'Ideal Fiber Reinforced Material' for unidirectional lamina with one inextensible direction [10].

To investigate the pure shear deformation behaviors of the new constitutive equation, 10×10 finite element meshes were used for a square piece of the FRT composite. The shear force was loaded on the four sides of the FRT composite. The left-lower corner node was constrained in all directions to prevent rigid body rotation. Dong et al. [5] used this problem to compare their material law to orthogonal constitutive equation using uni-directional lamina properties to model fabric reinforced composites.

Figure 3 shows the deformed shape calculated using the orthotropic material property provided as a material property option by the ABAQUS Explicit code. As shown in Figure 3(a), due to the elongation of the boundary, it is apparent that this material law could not simulate pure shear deformation. The orthogonal constitutive equation assumes the preservation of orthogonality during shear deformation. Figure 3(b) displays orthogonal material directions on the mesh which was updated using the rotation tensor, and thus in the case of near pure shear, without rigid body rotation, material directions did not change.

Figure 4 presents the deformed shape obtained under pure shear using the current constitutive equation. With the new constitutive equation, no change in the length of specimen boundary is observed (See Figures 4 (a)). This was possible because fiber directions were properly updated during the shear deformation as shown in Figure 4 (b). In Figures 5 (a) and (b), strains in two fiber directions, eventually non-orthogonal, are plotted with near zero values. The success with the pure shear simulation demonstrates that the current constitutive equation can predict the deformation behaviors of fabric reinforced thermoplastics at the high temperature whose main deformation mode is the scissoring behavior of two fiber families at intersection points.

The final example studies the deformation of the composite sheet during the forming process, which involves a heated hemispherical punch, a die(die chamber for hydroforming) and holder, and investigates the deformation behaviors of FRT composites. In this example, shell element(S3R in ABAQUS) is used for modeling the FRT blank. With the properties of the fabric reinforced composite with two preferred directions, this sheet-forming example will be used to demonstrate the feasibility of predicting the buckling behaviors of the FRT composite during forming.

A rectangular single ply of the FRT prepreg with 200mm length was formed by a hemispherical punch with 50.80mm in radius. Figure 6 shows three dimensional model for the composite and forming apparatus. The die (die chamber for hydroforming) is modeled by cylinderical shape with radius 52.50 mm and 6mm filet, while the blank holder has a circular shape of 100mm radius with the 3mm filet radius. Only one-quarter of the specimen was modeled considering the symmetry. Current example is based on the prototype sheet-hydroforming machine, which has been tested for composite sheet forming.

Figure 7 shows the deformed shape and fiber angle of the FRT with one layer by sheet-forming process. Around 45° degree between two fibers(warp and weft) and the die filet is severe distortion of fiber angle, which might be a cause of buckling as punch action proceeds further, so that quantitative investigation on this region is needed to evaluate the validity of the current forming condition.

The angle variation between two fibers (warp and weft) is investigated for evaluating the formability according to punching depth. The feasibility of the shaping operation is restricted by the limitation of this angle variation. Experimental research showed that maximum value of angle variation is close to 60° for the usual glass fiber fabrics used in the composite forming process [11]. With this criterion, it is concluded that current forming process and condition is sort of safe from shear buckling (Figure 8). In addition, angle deviation (the angle rotation of warp yarn from original position) is plotted in Figure 8, which is more severe as the punch moves. This fact advocates the current methodology of updating material law using deformation gradient according to the yarn movement. Figure 9 shows the strain evolution of the element experienced most severe angle variation, which intensifies that the deformation of woven fabric composite during stamping is driven by scissoring of two fibers.

Conclusions

Based on the homogenization method, a constitutive equation suitable for the thermoforming analysis of fabric reinforced thermoplastic composites has been developed. In this new constitutive equation, the microstructural information such as the fiber angle was introduced using internal variables. For validation purposes, in-plane simple shear, pure shear and three-dimensional deformation during the stamping operation were investigated. The solutions were obtained using the ABAQUS explicit finite element code by incorporating the current constitutive model into the code using the user material subroutine. The results demonstrated that the current model properly accounts for the effect of the differences in fiber strength and orientation on anisotropic behavior. As a result, shear dominant behaviors with no length change in pure shear as well as the prediction of the buckling of the FRT composite during forming were successfully simulated with the new constitutive equation.

Acknowledgements

The funding in support of this research through Composite Materials and Structures Center (CMSC) at Michigan State University is gratefully acknowledged.

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Table I. Properties of the fabric preform used in this study[8]: *unit:m

Material Properties		Parameters	
Young's modulus Of fibers(glass)	69 Gpa	$\tilde{E}^{\alpha}$	1.5E5 N
		$\tilde{E}^{\gamma}$	1.3E5 N
		E^{M}	0.001MPa
Structural Parameters of Fabric			
Yarn thickness	0.41 mm	$\vec{a}$	(0.0064, .0)*
Yarn width	5.33 mm	$\vec{b}$	(0., 0.0064)*
Yarn spacing	6.34 mm	A^{α}	2.19 mm^2
Ratio 0° - 90°	53:47	A^{β}	1.94 mm^2

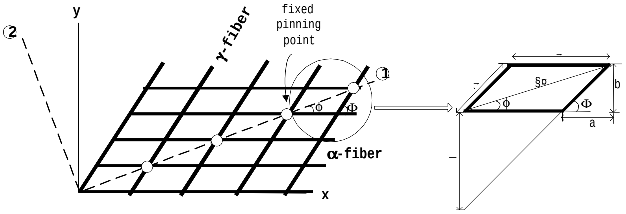


Figure 1. A structural unit of woven fabric reinforced composites.

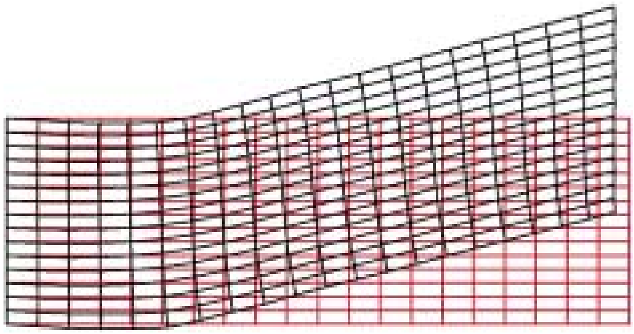
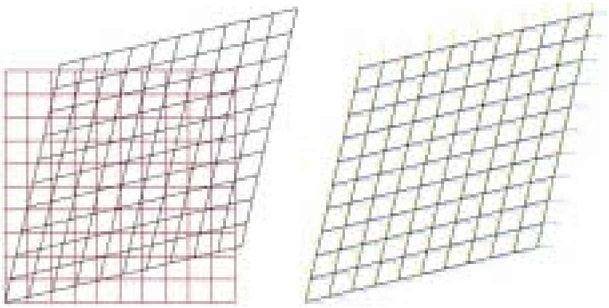
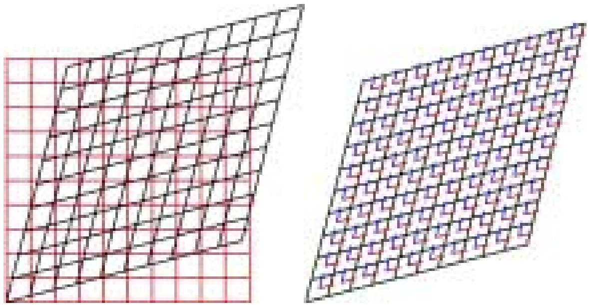


Figure 2. Deformed geometry of a beam due to shear loading



(a) (b)

Figure 3. Pure shear simulation using the orthotropic constitutive equation with the unidirectional lamina properties (a) deformed shape and (b) material direction ($E_{11} = 19\,\text{GPa}, E_{22} = 79\,\text{MPa}, \nu = 0.1, G = 0.01\,\text{MPa}$)



(a) (b)

Figure 4. Pure shear deformation with the new constitutive equation: (a) deformed shape and (b) fiber direction

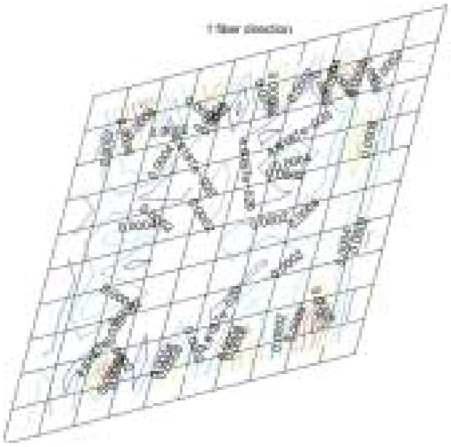


Figure 5-a. Strain distribution in 1 fiber direction by pure shear deformation with the new constitutive equation.

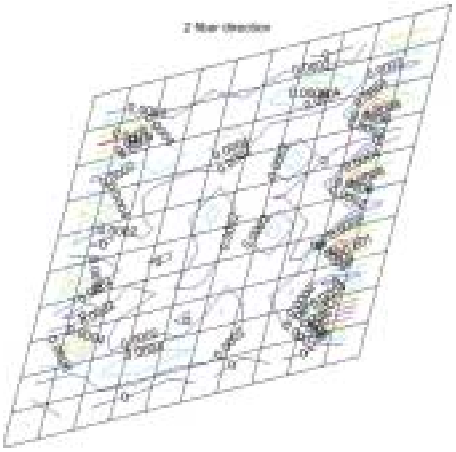


Figure 5-b. Strain distribution in 2 fiber direction by pure shear deformation with the new constitutive equation.

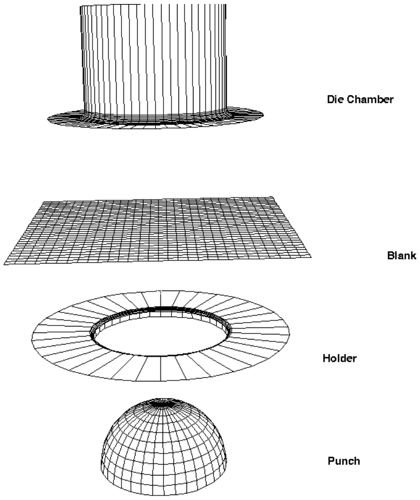


Figure 6. Finite element model for sheet forming simulation.

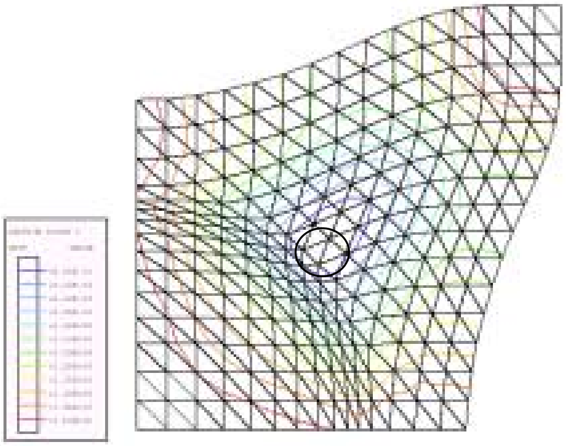


Figure 7. Deformed shape and fiber angle distribution of the blank by hemisphere punch.

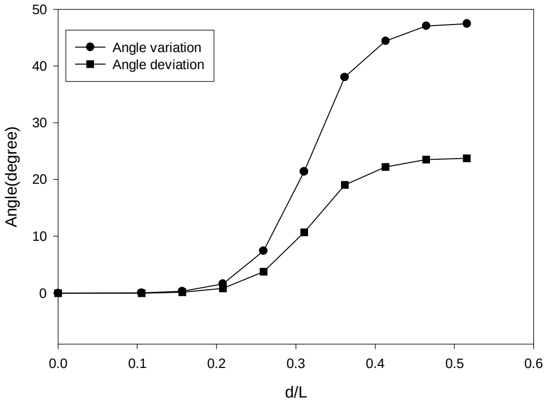


Figure 8. Fiber angle variation and deviation of the element in diagonal direction of blank intersecting die filet (O) according to the punching depth.

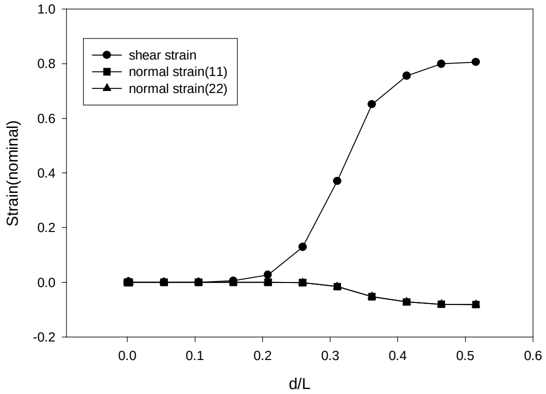


Figure 9. Strain evolution of the element in diagonal direction of the blank intersecting die filet (O) according to the punching depth.

KEY WORDS

Fabric Reinforced Thermoplastic Composite, Constitutive Equation, Anisotropy, Sheet Hydroforming.